# Phasor Estimation Using a Modified Sine Filter Combined with an Adaptive Mimic Filter

Kleber M. Silva and Bernard F. Küsel

***Abstract*— This paper presents a phasor estimation algorithm, which combines a modified sine filter with an adaptive mimic filter. The modified sine filter uses the recent and the previous data window to estimate the phasor. The key idea of the adaptive mimic filter is to readjust the parameters of the mimic filter to completely filter out the decaying dc component from faulted signals. The performance of the proposed algorithm was compared to those of other algorithms reported in the literature on the subject. Using a wide variety of EMTP-simulated data a statistical analysis algorithms performances was carried out. The obtained results indicate the proposed algorithm is less sensitive to decaying dc and high frequencies components which may appear following any disturbance in an electrical power system.**

***Keywords*— Phasor estimation, decaying DC component, digital mimic filter.**

## I. Introduction

MANY protective relaying functions use the phasors at the power system fundamental frequency [1]. The phasors are estimated from voltage and current sampled waveforms using digital filtering algorithms. These algorithms must have certain characteristics, such as: bandpass response about the fundamental frequency, decaying dc elimination, harmonic elimination and good transient behavior [2].

The most popular phasor estimation algorithms are the full and half cycle DFT-based algorithms [1]. It is well known the full cycle DFT (FCDFT) filters have better frequency responses than the half cycle DFT (HCDFT) filters, because the former eliminate all harmonics, whereas the latter do not eliminate even harmonics. In addition, HCDFT filters are quite sensitive to decaying dc and off-nominal frequency components [2].

Most efforts have been aimed to propose modifications in DFT-based algorithms [3]–[5]. The key idea of these algorithms is to perform the phasor correction based on the error in DFT output caused by the decaying dc component. In [3], the parameters of the decaying dc component are estimated using three successive FCDFT outputs. Modified FCDFT algorithms are proposed in [4], which are based on partial sums of one cycle of samples. These simplified algorithms perform well over a wide range of time constants. In [5], the decaying dc component effect on phasor estimation is suppressed using the difference between the outputs of the FCDFT for odd-sample-set and even-sample-set.

Another alternative to suppress the decaying DC component on phasor estimation named cosine filter was reported in [2], which uses the orthogonality between the present and the quarter-cycle earlier outputs of the full cycle cosine filter. However, it delays the response time by a quarter of a cycle.

In [6], the decaying dc component is removed using a digital mimic filter. The filter parameters are tuned to a particular time constant and in the case in which it is equal to the actual time constant of the signal, the mimic filter achieves the best performance. Otherwise, the larger the mismatch, the worse is the performance of the digital mimic filter.

In [7], the least error square (LES) algorithm is used to estimate the phasor at the fundamental frequency. The decaying dc component is modeled taken into account the first two terms of the Taylor series expansion. The LES algorithm performs well over a wide range of time constants, but not for small ones typically ranging from 0.1 to 0.5 cycles [4].

In this paper a phasor estimation algorithm is presented, which combines a modified sine filter with an adaptive mimic filter. The modified sine filter uses the recent and previous data window to estimate the phasor. The key idea of the adaptive mimic filter is to readjust the parameters of the mimic filter in order to completely filter out the decaying dc component from faulted signals. The performance of the proposed algorithm was compared to those of other algorithms reported in the literature on the subject. Using a wide variety of EMTP-simulated data a statistical analysis of the algorithms performances was carried out. The obtained results indicate the proposed algorithm is less sensitive to decaying dc and high frequencies components which may appear following any disturbance in an electrical power system.

## II. Proposed Phasor Estimation Algorithm

The frequency responses of the FCDFT filters are shown in Fig. 1. They are computed using a sampling rate of 16 samples per cycle. The frequency response $H_c$ is referred to as the response of the cosine filter and $H_s$ is referred to as the response of the sine filter. One can see that both responses have total harmonic rejection. It is is well-known the sine filter does not have the ramp rejection (double differentiation) capability, which is inherent to the cosine filter. As a result, the sine filter is quite sensitive to the decaying dc component effect [2]. On the other hand, the sine filter has better off-nominal and high frequency attenuation than the cosine filter, due to the lowest side lobes of its frequency response. Thus, based on these remarks the key idea of the proposed phasor estimation

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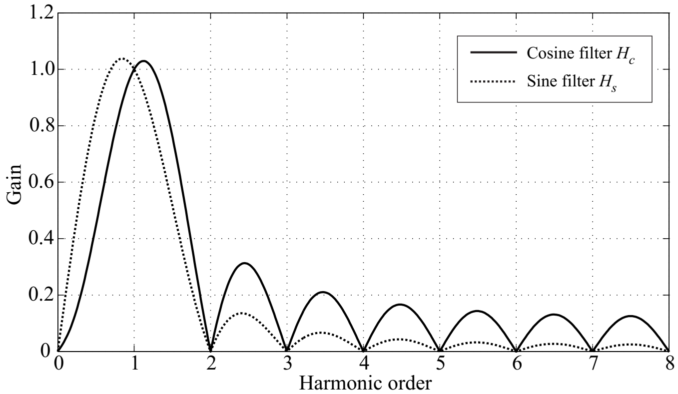



Fig. 1. Frequency response of the FCDFT filters.

algorithm arises: to combine a modified sine filter with an efficient strategy to filter out the decaying dc component, leading to a phasor estimation less sensitive to off-nominal, high-frequency and decaying dc components. The proposed algorithm is thoroughly discussed next.

### *A. Modified Sine Filter*

Consider a discrete signal $x(k)$ described as follows

$$x(k) = A_0\Gamma^k + \sum_{n=1}^{N/2} A_n \cos(nk\delta + \varphi_n) \tag{1}$$

where $A_n$ and $\varphi_n$ are the amplitude and the phase of the $n$-th harmonic component, respectively; $\Gamma = e^{-\triangle t/\tau}$ is the exponential term; $A_0$ and $\tau$ are the amplitude and the decaying time constant of the dc component; $\triangle t$ is the sampling interval; $\delta = 2\pi/N$ and $N$ is the number of samples within fundamental frequency cycle.

In order to present the modified sine filter fundamental, the decaying dc component of $x(k)$ is disregarded. Thus,the imaginary part of the phasor $\widehat{X}(k)$ can be computed by applying the full cycle sine filter to $x(k)$ [1]

$$X_{im}(k) = -\frac{2}{N}\sum_{r=1}^{N} x(k-N+r)\sin(r\delta) \ . \tag{2}$$

Substituting (1) in (2), one can verify that only the fundamental frequency component remains, since the full cycle sine filter has zero gain at all harmonic components and the decaying dc component was disregarded, thus

$$X_{im}(k) = -\frac{2}{N}\sum_{r=1}^{N} A_1 \cos\left[(k-N+r)\,\delta + \varphi_1\right]\sin(r\delta) \tag{3}$$

which can be written as

$$\begin{aligned} X_{im}(k) = &-\frac{2}{N}\sum_{r=1}^{N} A_1 \cos\left[(k-N+r)\,\delta\right]\cos\varphi_1 \sin(r\delta) \\ &+\frac{2}{N}\sum_{r=1}^{N} A_1 \sin\left[(k-N+r)\,\delta\right]\sin\varphi_1 \sin(r\delta) \end{aligned} \tag{4}$$

From trigonometric relationships

$$\sum_{r=1}^{N}\cos\left[(k-N+r)\,\delta\right]\sin(r\delta) = 0$$
$$\sum_{r=1}^{N}\sin\left[(k-N+r)\,\delta\right]\sin(r\delta) = \frac{N}{2}$$

resulting the imaginary part of the phasor $\widehat{X}(k)$ is

$$X_{im}(k) = A_1 \sin\varphi_1 \ . \tag{5}$$

The imaginary part of the previous phasor $\widehat{X}(k-1)$ can be computed as

$$X_{im}(k-1) = -\frac{2}{N}\sum_{r=1}^{N} x(k-N+r-1)\sin(r\delta) \ , \tag{6}$$

and by substituting (1) in (6)

$$X_{im}(k-1) = \frac{-2}{N}\sum_{r=1}^{N} A_1 \cos\left[(k-N+r-1)\,\delta + \varphi_1\right]\sin(r\delta) \tag{7}$$

which can be written as

$$\begin{aligned} X_{im}(k-1) = &\\ &-\frac{2}{N}\sum_{r=1}^{N} A_1 \cos\left[(k-N+r)\,\delta\right]\cos(\varphi_1-\delta)\sin(r\delta) \\ &+\frac{2}{N}\sum_{r=1}^{N} A_1 \sin\left[(k-N+r)\,\delta\right]\sin(\varphi_1-\delta)\sin(r\delta) \end{aligned} \tag{8}$$

Once again, from trigonometric relationships one can verify

$$\begin{aligned} X_{im}(k-1) &= A_1\sin(\varphi_1-\delta) \\ &= A_1\sin\varphi_1\cos\delta - A_1\cos\varphi_1\sin\delta \\ &= X_{im}(k)\cos\delta - X_{re}(k)\sin\delta \end{aligned} \tag{9}$$

then, the real part of the phasor $\widehat{X}(k)$ can be computed as

$$X_{re}(k) = \frac{X_{im}(k)\cos\delta - X_{im}(k-1)}{\sin\delta} \ . \tag{10}$$

Finally, the phasor $\widehat{X}(k)$ is obtained using (5) and (10)

$$\widehat{X}(k) = X_{re}(k) + jX_{im}(k). \tag{11}$$

### *B. On Combining the Digital Mimic Filter with the Modified Sine Filter*

According to the digital mimic filter principle, the fundamental phasor $\widehat{Y}(k)$ can be obtained without the harmful effects of the decaying dc component as (see Appendix I)

$$\widehat{Y}(k) = a\widehat{X}(k) + b\widehat{X}(k-1) \ , \tag{12}$$

where $\widehat{X}(k)$ and $\widehat{X}(k-1)$ are the phasors estimated at the time instants $k$ and $k-1$, respectively, and

$$a = K\,(1+\tau_d) \tag{13}$$

$$b = -K\tau_d \tag{14}$$

with $\tau_d$ and $K$ representing the time constant and the gain of the mimic filter. The gain $K$ must be one at the fundamental frequency

$$K = \sqrt{\frac{1}{\left[(1+\tau_d) - \tau_d \cos\delta\right]^2 + (\tau_d \sin\delta)^2}} \ . \tag{15}$$

From (12), the real and imaginary parts of the phasor $\widehat{Y}(k)$ can be computed as follows

$$Y_{re}(k) = aX_{re}(k) + bX_{re}(k-1) \tag{16}$$

$$Y_{im}(k) = aX_{im}(k) + bX_{im}(k-1) \tag{17}$$

Considering that the modified sine filter is used to estimate the phasor, one can obtain from (10) and (16)

$$\begin{aligned} Y_{re}(k) = a &\left[\frac{X_{im}(k)\cos\delta - X_{im}(k-1)}{\sin\delta}\right] \\ +b &\left[\frac{X_{im}(k-1)\cos\delta - X_{im}(k-2)}{\sin\delta}\right] \end{aligned} \tag{18}$$

which is rearranged as

$$\begin{aligned} &Y_{re}(k) = \frac{a}{\tan\delta} X_{im}(k) \\ &+ \left(\frac{b}{\tan\delta} - \frac{a}{\sin\delta}\right) X_{im}(k-1) - \frac{b}{\sin\delta} X_{im}(k-2) \end{aligned} \tag{19}$$

From (17) and (19), the real and imaginary parts of the fundamental phasor $\widehat{Y}(k)$ can be obtained using the combination of the modified sine filter and digital mimic filter as

$$\begin{bmatrix} Y_{re}(k) \\ Y_{im}(k) \end{bmatrix} = \mathbf{M} \cdot \begin{bmatrix} X_{im}(k) \\ X_{im}(k-1) \\ X_{im}(k-2) \end{bmatrix} \tag{20}$$

where

$$\mathbf{M} = \begin{bmatrix} \dfrac{a}{\tan\delta} & \dfrac{b}{\tan\delta} - \dfrac{a}{\sin\delta} & \dfrac{-b}{\sin\delta} \\ a & b & 0 \end{bmatrix} \tag{21}$$

The digital mimic filter causes a phase angle displacement in $\widehat{Y}(k)$, which must be corrected. It is performed using a linear transformation of rotation, resulting in phasor $\widehat{Y}^*(k)$

$$\begin{bmatrix} Y^*_{re}(k) \\ Y^*_{im}(k) \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \cdot \begin{bmatrix} Y_{re}(k) \\ Y_{im}(k) \end{bmatrix} \tag{22}$$

where $\phi$ is the phase angle displacement caused by the digital mimic filter

$$\phi = \arctan\left[\frac{\tau_d \sin\delta}{(1+\tau_d) - \tau_d\cos\delta}\right] \ . \tag{23}$$

### *C. The Adaptive Scheme to Readjust the Digital Mimic Filter Parameters*

As aforementioned, in the case in which the digital mimic filter parameters are tuned to the actual time constant of the signal, the mimic filter achieves the best performance on decaying dc component removal. Thus, the key idea here is to estimate the decaying time constant $\tau$ of the dc component that arises in fault signals and use this estimation to readjust the mimic filter parameters $\tau_d$ and $K$ . In order to estimate $\tau$, firstly the exponential term $\Gamma$ is estimated.

Consider a discrete signal $x(k)$ of the form described by (1) with the decaying dc component. Thus, the following partial sum terms can be defined [4]:

$$PS_1 = \sum_{k=1}^{N/2} x(2k-1) \tag{24}$$

$$PS_2 = \sum_{k=1}^{N/2} x(2k) \ . \tag{25}$$

From trigonometric relationships and algebraic manipulations in (24) and (25), $PS_1$ and $PS_2$ can be solved as

$$PS_1 = A_0 \frac{\Gamma\left(\Gamma^N - 1\right)}{\Gamma^2 - 1} \tag{26}$$

$$PS_2 = A_0 \frac{\Gamma^2\left(\Gamma^N - 1\right)}{\Gamma^2 - 1} \ . \tag{27}$$

From (26) and (27), $\Gamma$ can be computed as follows

$$\Gamma = \frac{PS_2}{PS_1} \ . \tag{28}$$

The time constant $\tau$ can be obtained approximating the exponential term $\Gamma$ using the first two terms of its Taylor series expansion, accordingly

$$\tau = \frac{\triangle t}{1-\Gamma} \ . \tag{29}$$

Physically, $\tau$ does not change during a given transient. However, the estimator (28) may lead to unrealistic values for $\Gamma$ in the first few samples. To overcome this drawback, $\tau$ is forced to stay in between $\tau_{min} = 0.5$ cycles and $\tau_{max} = 5$ cycles, which are in accordance with the typical range of time constant values [6].

Averaging the estimated values of $\tau$ over a number of samples leads to further damping of unwanted oscillations. Simulation results has shown that the use of two samples average leads to good results.

For each new value of $\tau$, the readjustment of the digital mimic filter parameter is performed. The value of $\tau_d$ is expressed in number of samples, in such way that it can be computed as follows

$$\tau_d = round\left(\tau/\triangle t\right) \ , \tag{30}$$

where the operator $round(\cdot)$ rounds a float point number to the nearest integers. Then, the gain of the mimic filter for the fundamental frequency is readjusted using (15). Finally, the new values of the variables $a$ and $b$ are computed using (13) and (14), thereby the coefficients of the matrix $\mathbf{M}$ described by (21) are readjusted.

### D. Summary of the Proposed Algorithm

The proposed phasor estimation algorithm can be summarized as shown in Fig. 2. For each new sample of $x(k)$, the imaginary part $X_{im}(k)$ of $\widehat{X}(k)$ is estimated using the full cycle sine filter described by (2). The exponential term $\Gamma$ and the decaying time constant $\tau$ of the signal $x(k)$ are obtained using (28) and (29), thereby the digital mimic filter parameters are readjusted. The time constant $\tau_d$ and the gain $K$ are recalculated using (30) and (15). Then, the parameters $a$ and $b$ are readjusted using (13) and (14). The phasor $\widehat{Y}(k)$ is computed using (20) without the harmful effects of the decaying dc component, but its phase angle needs to be corrected to remove the phase angle displacement caused by the mimic filter using (22) and (23), resulting the fundamental phasor $\widehat{Y}^*(k)$.

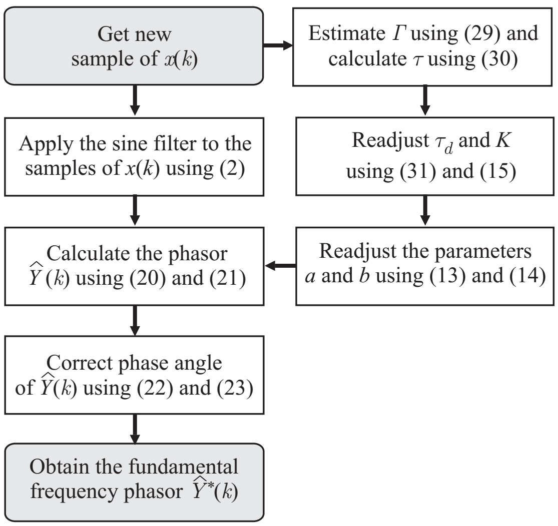



Fig. 2. Flowchart of the proposed phasor estimation algorithm.

## III. Performance Evaluation

The performance of the proposed algorithm was compared to those of the simplified algorithm 1 reported in [4] (here named as modified FCDFT), the LES algorithm [7] and the cosine filter algorithm [2]. The obtained results are discussed next.

The time responses analysis of phasor estimation algorithms is important to verify their performances during the transient interval in which data windows contains both pre-fault and fault samples. Thus, some important characteristics to digital relaying are pointed out, such as its speed and accuracy.

To evaluate time response ATP simulated data were used. The simulations was carried out using a sampling rate of 160 samples per cycle. The output signal was preprocessed using a third order Butterworth low-pass filter with cutoff frequency at 180 Hz. Then, the output signal was resampled at 16 samples per cycle. Resampled signals were used to evaluate the performance of the phasor estimation algorithms.

The basic power system model shown in Fig. 3 was taken into account to generate fault data using ATP (Alternative Transients Program) to test the performance of the algorithms

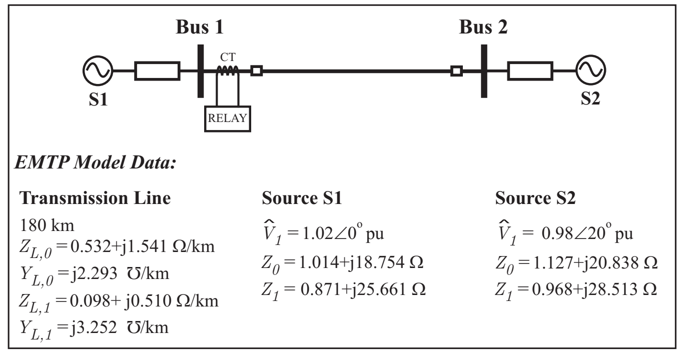



Fig. 3. Single line diagram of the power system for testing.

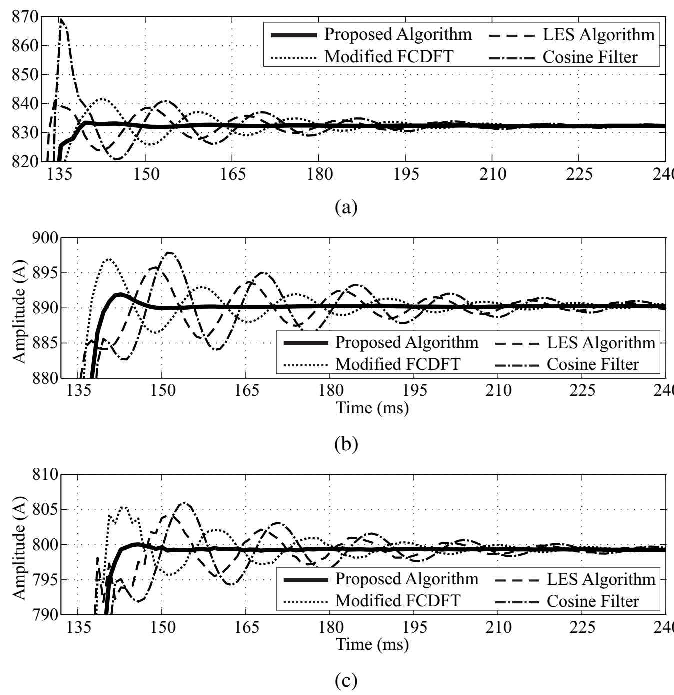



Fig. 4. Fundamental phasor amplitude: (a) phase C current for an BC fault (40 km far away from bus 1, with incidence angle of $60^0$ and fault resistance of 10 Ω); (b) phase A current for an ACG fault (90 km far away from bus 1, with incidence angle of $30^0$ and fault resistance of 30 Ω); (c) phase B current for an BCG fault (140 km far away from bus 1, with incidence angle of $90^0$ and fault resistance of 30 Ω).

on decaying dc component removal. The sources and components subscripts "0" and "1" correspond to zero sequence and positive sequence values, respectively. There are two 230 kV ideal sources S1 and S2 and one transmission line 180 km long. The current transformer (CT) shown in the figure was also included in ATP simulations. Its model and parameters are those reported by the IEEE Power System Relay Committee in [8]. Here, the tap is chosen in such way that CT core never saturates for any evaluated fault current.

In Figs. 4 the fundamental phasor amplitude for two different faults simulated in ATP are shown. In Fig. 4(a), it is shown the amplitude of the phase C current for a phase-to-phase fault between phases B and C (40 km far away from bus 1, with incidence angle of $60^0$ and fault resistance of 10 Ω). In Fig. 4(b) is shown the amplitude of the phase A current for a phase-to-phase to ground fault between phases A and C (90

TABLE I
SIMULATION VARIABLES USED TO SIMULATE FAULTS.

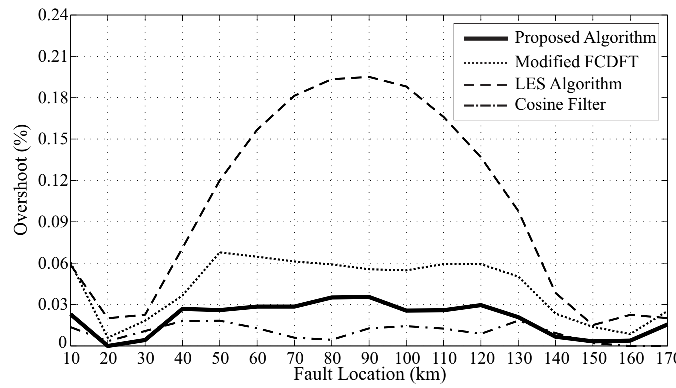
| Simulation variables | Chosen Values |
|---|---|
| Fault location (km) | 10, 20, 30, ..., 150,160 and 170 |
| Fault resistance (Ω) | Phase-Phase: 1, 5 and 10<br>Phase-Ground: 10, 20 and 30 |
| Incidence angle (°) | 30, 60 and 90 |
| Source impedance<br>(% of the nominal values) | Source $S$: 10, 100 and 1000<br>Source $R$: 10, 100 and 1000 |
| Fault type | AG-BG-CG-AB-AC-BC<br>ABG-ACG-BCG-ABC |

km far away from bus 1, with incidence angle of $30^0$ and fault resistance of 30 Ω). In Fig. 4(c) is shown the amplitude of the phase B current for a phase-to-phase to ground fault between phases B and C (140 km far away from bus 1, with incidence angle of $90^0$ and fault resistance of 30 Ω). One can see that the proposed algorithm leads to the smallest overshoot.

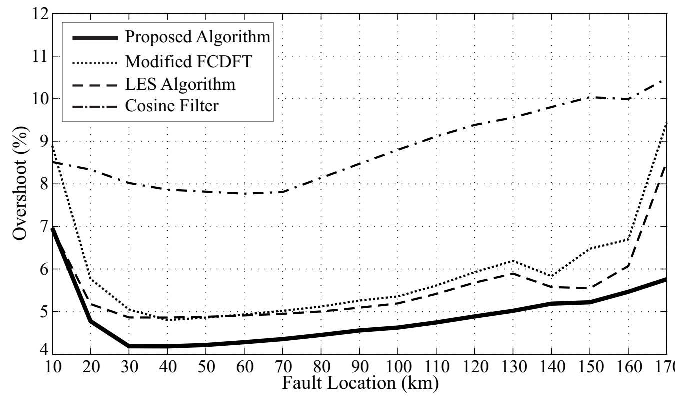
To verify the robustness of the proposed algorithm, extensive fault simulations under various fault conditions were performed. The following simulation variables were taken into account: fault location, fault resistance, fault incidence angle (reference at the voltage in phase A of the source S1), source impedance (or source strength) and fault type. The chosen values for these variables are summarized in Tab. I.

From the combination of the variables summarized in Tab. I a total of 13770 faults were simulated. A statistical analysis of the performances of the evaluated algorithms on decaying DC component elimination was carried out. The total of 810 faults were simulated at each 10 km of the transmission line length. The minimum, maximum and average overshoot in the amplitude estimation of the current fundamental phasors were obtained for each fault location. These results are plotted in Figs. 5. The proposed algorithm worst performance was 6,9% at 10 km, but even so its maximum overshoot was smaller than those of other algorithms for the remaining fault locations. The average overshoot profile of the proposed algorithm is almost flat at 0,75%, leading to the best performance among the evaluated algorithms. The modified FCDFT presents the second best performance, followed by the LES algorithm and the cosine filter algorithm, respectively.

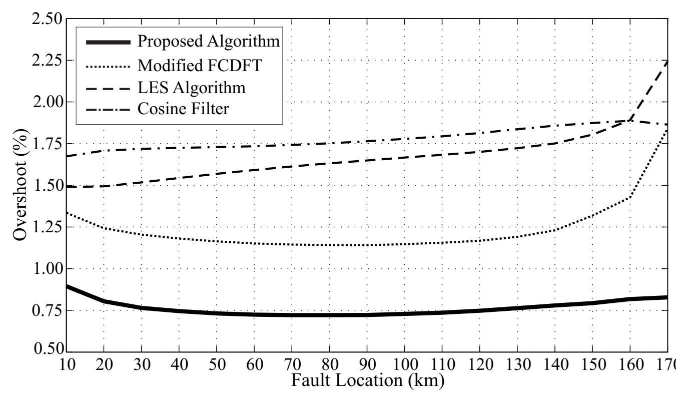
The performance of the algorithms can also be evaluated by the analysis of the cumulative frequency polygon shown in Fig. 6, which is a plot of the percentage of faults against the maximum overshoot in amplitude estimation of the current phasor. The proposed algorithm presents the best performance, providing the smallest overshoot in the most faults. Once more, the modified FCDFT presents the second best performance, followed by the LES algorithm and the cosine filter algorithm. For example, the proposed algorithm provides an overshoot equal to or smaller than 1,0% for about 80% of faults. Whereas, this percentage for the modified FCDFT, the LES algorithm and the cosine filter algorithm is about 48%, 30% and 40%, respectively, and so forth.




(a)




(b)




(c)

Fig. 5. (a) Minimum, (b) maximum and (c) average overshoot in current phasor amplitude estimation for each fault location.

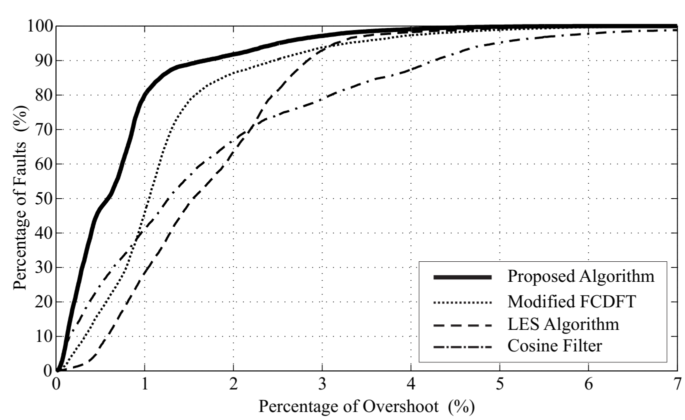



Fig. 6. The cumulative frequency polygon plotting the percentage of faults against the maximum overshoot in current phasor amplitude estimation.

## IV. Conclusions

This paper presents a phasor estimation algorithm. Its key idea is combine a modified sine filter with an efficient strategy to filter out the decaying dc component. The modified sine filter uses the recent and previous data window to estimate the phasor. The digital mimic parameters are adaptively readjusted in order to completely filter out the decaying dc component from faulted signals. As a result, the phasor estimation is less sensitive to off-nominal, high-frequency and decaying dc components.

The performance of the proposed algorithm was compared with those of other algorithms reported in the literature on the subject. A wide variety of ATP-simulated data was also used to analyze the performance of the algorithms. A statistical analysis was carried out. The obtained results indicate that the proposed algorithm leads to the smallest overshoots for most cases.

In accordance with the results discussed in this paper, the proposed algorithm shows great promise to be used in power system protection applications.

## Appendix I
## The Traditional Digital Mimic Circuit

According to the mimic circuit principle, if an exponentially decaying dc current has to pass through a mimic circuit consisting of an impedance of the form

$$K\left(1+s\tau\right) \ , \tag{A.1}$$

the voltage across the impedance will be only a dc constant, if $\tau$ is equal to the decaying time constant of the current waveform. The digital version of this equation is known as the digital mimic filter equation [6]

$$K\left[\left(1+\tau_d\right)-\tau_d z^{-1}\right] \ , \tag{A.2}$$

where $\tau_d$ is expressed in number of samples.

Consider a discrete signal $x(k)$ computed as

$$x(k)=A_0\Gamma^k+\sum_{n=1}^{N/2}A_n\cos\left(nk\delta+\varphi_n\right) \tag{A.3}$$

where $\Gamma=e^{-\triangle t/\tau}$ is the exponential term; $A_0$ and $\tau$ are the amplitude and the time constant of the decaying dc component; $N$ the number of samples per fundamental frequency cycle; $\triangle t$ is the sampling interval; and $\delta=2\pi/N$.

Applying the digital mimic filter to $x(k)$

$$y(k)=K\left[\left(1+\tau_d\right)x(k)-\tau_d x(k-1)\right] \ . \tag{A.4}$$

The gain $K$ must be one at the fundamental frequency

$$K=\sqrt{\frac{1}{\left[\left(1+\tau_d\right)-\tau_d\cos\delta\right]^2+\left(\tau_d\sin\delta\right)^2}} \tag{A.5}$$

In the case of $\tau_d$ is equal to the time constant of the decaying dc component presents in the input signal $x(k)$, the output signal $y(k)$ consists of a dc constant added to the $N/2$ order harmonic components.

The phasor $\widehat{Y}(k)$ of the discrete signal $y(k)$ can be estimated by applying a phasor estimation algorithm to (A.4), in such way that

$$\widehat{Y}(k)=K\left[\left(1+\tau_d\right)\widehat{X}(k)-\tau_d\widehat{X}(k-1)\right] \ , \tag{A.6}$$

where $\widehat{X}(k)$ is the phasor of $x(k)$.

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